Exergy Optimized Wastewater Heat Recovery: Minimizing Losses and Maximizing Performance

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ABSTRACT

In this project a system to utilize the heat that would otherwise be destroyed in warm water going down the drain has been optimized. Both the quantity and quality of the energy flows are considered using exergy analysis. The system recovers the heat using a batch process with an insulated tank containing a heat exchanger. The analysis is based on statistical annual hot water usage profiles. The system shows that the exergy available in warm wastewater can be optimized with specific tank size and heat exchanger flow rate to the exergy the extraction. This gives an energy recovery of 3000 kWh or 10% of the U.S. single-family residential household demand or over 50% of annual hot water demand. A complete system would utilize this optimized exergy output to minimize the temperature lift required by a heat pump. This would create an integrated low exergy space and water heating system. The project theory is a part of the IEA ECBCS Annex 49, and also collaboration has been setup with Geberit AG to eventually bring a product to market.

INTRODUCTION

Motivation

The fact that buildings are responsible for two-thirds of electricity consumption and one-third of greenhouse gas emissions was first shown by Roodman and Lenssen (1993). More recently conglomerations of data from residential and commercial sectors has shown that when considered as a whole, the building sector is actually responsible for over half of global greenhouse gas emissions (Mazria, 2007). This provides a fundamental and substantial motivation to reduce the energy demand and resulting emissions. Buildings, with their relatively long lifespan, need have new systems made available quickly to increase their performance; each improvement will have a huge potential for reduced energy consumption when the entire lifespan of a building is considered.

The heating of buildings has become a focal point of research into creating high performance buildings. Still, this focus is often limited to only space heating. Not only does each aspect of heating have to be recognized, but also ways to integrate and optimize these systems must be considered. This should all be done without overlooking the second law of thermodynamics and entropy production by utilizing the concept of exergy analysis.

Exergy is an important tool for the improvement of buildings. It pinpoints areas where not just energy might be wasted, but also the differences between high temperature and thus high quality sources versus low temperature and thus low quality sources. Every heat transfer in a building generates entropy and thus destroys exergy; therefore this concept should be used along with energy balances and optimization to create better buildings

For performance improvements of buildings to be made one must understand their fundamental flows. Like organisms they breathe air in and exhaust it out, they utilize materials and water and waste the byproducts, and energy is input for these and other functions. Unlike buildings organisms have had eons to integrate and optimize their systems while buildings are relatively young in design. This gives them plenty of room for improvement. These improvements can be best done by integrating systems, and by paying close attention to what is lost in the system that could still be used.

One area that has a definite lack of attention is the water flow. This is probably due to both the current focus on office buildings in research, and the smaller scale of residential systems. Still, the most recent Residential Energy Consumption Survey in the United States showed that hot water production represents 17% of total energy consumption (2001). In well-insulated high performance buildings, now becoming more common, the hot water can easily account for over half of the energy demand. In virtually every case the high temperature water used, with its high exergetic value, is flushed directly out of the building. Exhaust air heat recovery systems are becoming more common, but if the air flow is to be recovered in a building, so should the water flow.

Summary

This study presents an exergy analysis of a wastewater heat recovery system and its potential impact on building operation. A model is described that uses statistically generated data of hot water usage data for a year. The model finds the optimal heat extraction at the highest possible temperatures. The utilization of this exergy in an integrated system will be presented for the case of a "low exergy" building. Therefore the system will incorporate a heat pump, which will service a low temperature heating system as well as the hot water supply, and incorporating decentralized ventilation. The operation of such a system is will be approximated along with the potential impact of wastewater heat recovery

Using this wastewater heat recovery system minimizes exergy destruction, and leads to a significant possible reduction in domestic hot water energy demand.

BACKGROUND

Exergy

Exergy is a combination of the basic energy and entropy balances as defined by the first and second laws of thermodynamics. This makes it possible to consider energy quantity as well as quality in one term. This is done relative to the reference environment in which it sits with fixed temperature, T_0, and pressure, p_0. This is considered to be a better way to improve energy systems and make better energy policy (Rosen, 2008)

In a heating system exergy, Ex, is defined by the heat or energy, Q, which is adjusted by a term accounting for the change in entropy, Δs, of the system in the reference environment, T_0, as given in Equation 1 (Ahern, 1980).

$$Ex = Q - T_0 \cdot \Delta s \qquad (1)$$

For an incompressible fluid with mass flow rate, mdot, the exergy term, Ex, can be approximated by assuming a constant heat capacity, c_p. The entropy term can be estimated by the natural logarithm of the ratio of the temperature change, T_H/T_C, as shown in Equation 2 (Schmidt, 2004).

$$Ex = mdot \cdot c_p \cdot [(T_H - T_C) - T_0 \ln(T_H/T_C)] \qquad (2)$$

Exergy is useful for the optimization of thermodynamic systems. It describes the not just the quantity of energy in a system, but also the quality. This quality is evaluated by looking at the system relative to the surrounding environmental conditions. If the system has a high relative temperature or pressure as compared to its surroundings, then it also has a higher potential to perform work. This relative value is captured in the concept of exergy. (Ahern, 1980) (Moran, 2000)

The definition of the external environment, T_0, is fixed for most systems operating in controlled environments, but for large scale systems like buildings it can be assumed to be fixed for individual systems, or it can be taken to be the average outside conditions or the standard design conditions. (Schmidt, 2004).

Another term that is often used along with exergy is anergy. This refers to exergy that has been destroyed or is at the environmental state. It can no longer do work relative to the defined environment, and therefore another name for the environmental state is the dead state. Although work cannot be created from this state, work can be done in a thermodynamic cycle to extract anergy from the dead state as is done by heat pumps.

Low Exergy Buildings

In terms of exergy, buildings inherently have low exergy. A comfortable room temperature is not of very high quality relative to the outside environment. Therefore one of the first themes of low exergy building systems is the avoidance of high temperature heat sources like combustion, and the exploitation of low temperature high surface area heating systems.

Low exergy systems utilize the concept of both low temperature heating as well as high temperature cooling. This minimizes the temperature gradient between the room air and the heat source, thus minimizing exergy destruction. Adequate heating or cooling to be supplied with good insulation and a large surface area systems like TABS or chilled-beams. This allows the small temperature gradients to supply adequate conditioning. The conditioning is ideally provided by a heat pump where the low temperature requirement maximizes its performance. An extensive overview is found in the IEA Annex 37 Guidebook (2003) and at www.lowex.net. It is being further developed in the IEA ECBCS Annex 49 www.annex49.com.

Heat Pumps

A heat pump can move heat from a cool source to a warmer sink using a thermodynamic cycle. The laws of thermodynamics govern the performance, which is the amount of heat that can be moved per amount of energy input into the system. This performance is the coefficient of performance (COP) and it has a theoretical maximum defined by a reversible Carnot cycle given in Equation 3 (Moran, 2000).

$$COP = T_H / (T_H - T_C) \qquad (3)$$

A real heat pump has losses that lower its COP to a fraction of the ideal Carnot. Still, it is clear that the potential of heat pump performance is dependent on the temperature lift it must provide. The exergetic performance of heat pumps has been studied by Gasser et. al. (2008), Ozgener (2007), and Bilgen (2002) among others, which show the potential for better optimization of heat pump systems through the use of exergy analysis.

The use of heat pumps for the production of hot water is well known (IEA Heat Pump Centre, 1993). The application of heat pumps for hot water production is expanding as fossil fuels become more costly (Waide, 2008). New methods of measuring seasonal efficiency of integrated hot water and space conditioning heat pumps have been developed (IEA Heat Pump Centre, 2006).

How Water Demand

Hot water is produced largely in domestic systems. These range from small single-family homes to multi-family complexes and hotels. In order to realistically consider the potential of using energy from hot wastewater, one must consider how and when hot wastewater is produced. Unlike ventilation, the usage is sporadic and unpredictable (Shove, 2003). For an accurate look at flow of energy and exergy in hot water, realistic usage like that of Jordan (2003) should be considered.

The recovery of energy from warm wastewater has been considered, but only for very large-scale systems (Schmid, 2008). Technology has been developed for hotel systems and for sewer systems (Zogg, 2008). But these capture only the lower exergy level mixed wastewater and overlook the value of high temperature recovery in small-scale systems.

METHODS

Data Acquisition

The data used for the simulation of the hot water usage came from a simulation engine developed at the University of Kassel (Jordan, 2003). This engine was used to produce usage profiles based on statistics gathered at the US National Renewable Energies Laboratories (NREL). The data was produced from the engine based on daily usage profiles for showers, bathes, sinks, laundry, and dishwashers end-uses (Hendron, 2007). Random usage data was generated at 6-minute intervals for each end-use that fit the statistically described profiles. The hot water demand was simulated for a two, three, or four bedroom residence. There is data for pure hot consumption or for the hot-cold for mixed end-uses. The temperatures of the usage are taken from Hendron (2007). The data for four bedrooms was used for the heat recovery model, and the entire year was compiled into one input for simulation in Matlab.

Analysis

The flow of warm wastewater is simulated over time from the previously described data. This is sent into a simulated recovery tank with a set diameter, volume, and wall heat transfer coefficient. The tank contains a heat exchanger having a flow rate, pipe diameter and fixed supply temperature of 10°C, and is modeled in a spiral. The spiral width is sized relative to the tank diameter, and the spacing between turns is relative to the pipe diameter

At each time step the simulation checks if a hot water event occurred and the quantity entering the tank. The temperature of the incoming water is adjusted from the given values (Hedron, 2007) so that losses during flow to the tank and losses during use, are considered. These are estimated to be 5, 3, 2, 5 and 2 percent for bath, shower, sink, clothes and dishes respectively.

If an event has occurred, the new volume of the tank is calculated. If the tank would be filled past capacity, an overflow value is triggered. It removes liquid from the bottom of the tank, so if the new volume is greater than the capacity, the previous water is removed to make space for new input.

New events are combined using an energy balance between the incoming flow and current volume to determine the new temperature of the tank, assuming it is completely mixed. The heat extraction by the heat exchanger is modeled as a laminar flow through a pipe with constant surface temperature equal to the tank temperature (Wiley, 2002). The heat extracted from the tank and the heat-loss from the walls are removed from the tank using an energy balance over the 6 minute time-step. This provides the new tank temperature. If the temperature has dropped below a set point, the tank is flushed completely.

The amount of exergy available from the wastewater is calculated from equation 2 along with the amount of heat extracted from the energy balance. The reference state for the exergy comparison is 1 atm and 5 degrees Celsius.

The heat pump is assumed to have a given performance. The operating temperature and pressure of the evaporator temperature can be raised using the heat recovered. Thus the heat pump COP can be improved based on the simple Carnot (equation 3) multiplied by a performance factor of typical exergetic efficiencies of heat pumps (Gasser, 2008). This provides a rough estimation of the performance increase that could be obtained in a heat pump from the reduced exergy needed to provide the high temperature lift for water heating. Finally the impact for the global building sector was considered based on hot water usage and energy demand of buildings.

RESULTS

Recovery of Wastewater Exergy

The simulated operation of a 400 L recovery tank for a year with 6-minute time-steps is shown in Figure 1. This presents an overview of the dynamics of the operation for the course of the model year. The amount of activity is clear and the two vacation periods that are generated for the hot water usage profile are also obvious.

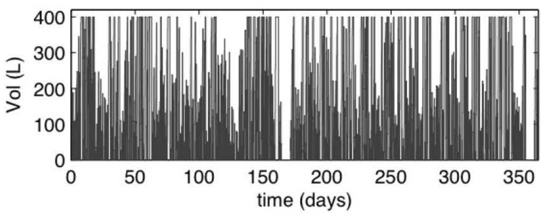

Figure 1. Volume in the recovery tank over the course of the modeled year with the month of January highlighted.

In order to highlight more details, the month of January is expanded from Figure 1 in Figure 2. Three plots are shown. The top shows the volume in the tank. The bottom plot shows the temperature in the tank.

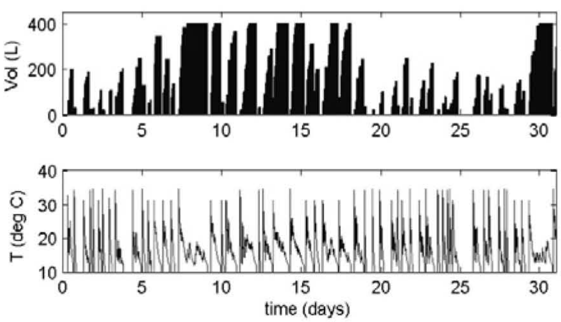

Figure 2. January data for the recovery tank total volume (grey) and overflow volume (black) on top, tank temperature in the middle, and exergy recovered on the bottom.

Figure 2 shows that after the tank is filled, it generally stays full for a few hours as the heat is removed. Multiple events keep the tank full from about day 7 to about day 10, and the capacity if filled so some water is flushed before being cooled to the flushing set point temperature. The temperature drops relatively quickly to around 20°C initially after a hot water event. It then slowly decreases until it is flushed or another event occurs.

The energy and exergy output from the recovery tank was analyzed while the properties of the system were adjusted to maximize the recovery. It was found that the heat exchanger flow rate and the tank size had the largest influence on the performance of the system. These aspects were probed and a maximum point for exergy recovery was found, shown in Figure 3 and Figure 4.

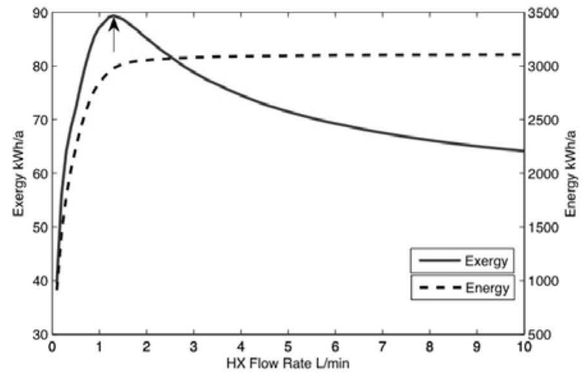

Figure 3: Total exergy recovered over the year versus the heat exchanger flow rate. With the maximum of about 90 kWh/a of exergy pointed out at 1.3 L/min.

In Figure 3 there is a definitive maximum recovery at a flow rate of 1.3 L/min through the heat exchanger. The energy perspective does not show this maximum potential, although this peak is found near to where the asymptotic maximum value for energy output is located.

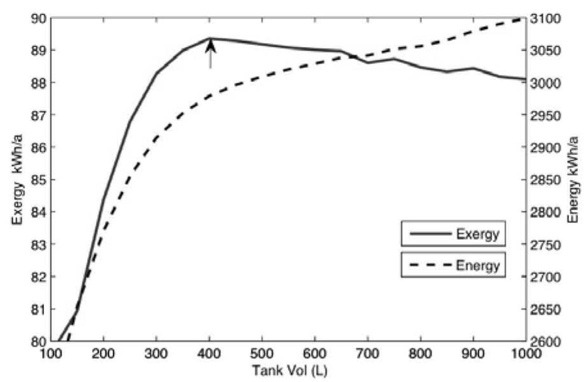

Figure 4. Total exergy recovered over the year versus the size of the tank for the flow rate of 1.3 L/min.

In Figure 4 there is also a maximum for exergy recovery based on tank size that is not shown by the energy output. In this case it is less pronounced, and it is for a 400 L tank. In this case the energy output continues to rise for larger tanks, but not at a significant rate.

Both maximums were consistent when adjusting other system parameters. The maximum recovery was 89 kWh of exergy and 3000 kWh of energy. The energy demand reported by Hendron (2007) for this hot water usage year scenario was 4800 kWh and the tank model simulation showed the total input energy of hot water was 4400 kWh for the year, 3000 kWh of which were recovered. The simulation provided the total exergy of the annual hot water production at 350 kWh.

On the basis of energy the 3000 kWh is about 70% of the energy in the hot water use for a year. From an exergy perspective 85 kWh are recovered compared to the 350 kWh supplied. This is only 25% because the temperature recovered is lower than the temperature supplied, thus the exergy describes a loss in quality. But this view of quality allows for these optimal points to be discovered, whereby more high quality energy can be recovered at higher temperatures not just to be transferred to a heat pump, but also to improve its performance.

Integrated Air and Water Recovery System

The recovery can be part of integrated domestic hot water and space conditioning heat pump system. There are many options readily available (IEA Heat Pump Center, 1993). But the valuable potential shown above of exergy recovery from wastewater for use in the heat pump must still be integrated. This is optimally done by directly reducing the exergy demand of the heat pump. Ideally a heat pump with a compressor that could operate at two different temperature lifts could be designed. The heat pump could then provide low temperature lift space heating, and the heat recovery from exhaust air and the wastewater could allow a low temperature lift for water heating as well. In collaboration with the Lucerne University of Applied Science and Arts these new heat pump concepts are under development.

Costs and Savings

A simple estimation of the increase in heat pump performance can be achieved by substituting the evaporator temperature with the recovery temperature. For a typical ground source heat pump the incoming temperature is about 10°C. The average temperature coming out of the heat exchanger was 15°C with a range going up to 30°C.

For a typical exergetic efficiency of 0.4 (Gasser, 2008), the COP of typical ground source heat pumps would go from about 3 to 3.3 for the average supply. Depending on how the dynamic heat pump system can be modulated for different inputs, the higher temperature outputs could increase the COP to close to 5. If a heat pump were providing 10,000 kWh of heating, the base case would reduce the electricity needed from 3300 kWh to 3000 kWh or to as little as 2000 kWh for the maximum heat recovery.

The cost of operation depends largely on the design of the heat pump. The pumping costs for the flow rates determined here are insignificant. The primary costs will depend on the heat exchanger and tank design, production, and installation costs.

Potential Building Sector Impact

In the United states, 21% of primary energy is consumed by the residential sector (EIA, 2006). Of this 17% (1.7 Quads or 1.8 EJ) is used for hot water heating (RECS, 2001). Virtually all of this energy is currently sent down the drain. For water heating in US households, 39% of heaters are electric and 53% are natural gas fired (RECS 2005). Both the electricity and the natural gas have high exergetic value. A heat pump with a COP of 3 can supply 3 units of energy for every one unit of power (i.e. electricity) supplied to the compressor. An electric heater and a gas heater have a maximum 1 unit of energy for their one unit of electrical and chemical energy respectively. Currently the electricity in the US (EIA, 2006) requires 4 units of fossil energy to be combusted at the power plant. Therefore it is clear that electrical heaters make absolutely no sense and should be replaced with heat pumps. On the other hand gas heaters use their primary energy directly and electric heat pumps still incur electricity transport and generation losses. Thus, only high performance heat pumps with COP>4 have a lower primary energy demand, although the supply of electricity can be easily changed to a renewable or improved supply. Still, High performance heat pumps can have high COP that greatly outperform the primary exergy requirements of any gas or electric heating system, and there is an opportunity to go further with system that integrate recovery from waste heat sources like wastewater.

This potential is not only found in the US, but also in the European Union (EHPA, 2008) and Japan (Takahashi, 2008). In the EU the residential sector accounts for 26% of energy demand with 14% coming from hot water heating, and a strong push toward more efficient heat pump technology (EEA, 2008). In Japan, the strongest effort is being made where a hot water heat pump has been developed with a COP of 4.9 and is being widely implemented, and Japan hopes to achieve 130 million tons of CO2 equivalent greenhouse gas reductions by implementing this technology (Takahashi, 2008).

CONCLUSIONS

Overall System Potential

The potential recovery of exergy from hot wastewater has been analyzed. There is an optimal savings in a year for a typical 4-bedroom residence of 89 kWh of exergy. This leads to 3000 kWh or 70% recovery of annual hot water heat, and is a maximized 25% recovery of exergy. A potential concept for integration of this system is presented. An estimate is made for performance increase of 3 to from 3.3-5 in COP. In this preliminary study on the potential of hot water exergy recovery the large potential impact of heat pumps with this improved performance has been detailed.

Applications

This research is part of work in the IEA (International Energy Agency) ECBCS (Energy Conservation in Buildings and Community Systems) Annex 49 (www.annex49.com). The work provides the basis for the development of new heat recovery systems that consider exergy. Collaboration is also underway with the largest sanitary systems firm in Europe, Geberit AG, They will use the theory and concept developed here to produce a product for market. The goal is to have a pilot project ready to be implemented in a 4 floor, 4 apartment, building project in Zurich that will begin construction in 2009.

Future Work

Further analysis will include better modeling of tank stratification dynamics as well as heat exchanger characteristics using better approximations of the system such as a better finite difference for the transient temperatures between time steps. Also, a wider range of usage profiles should used to understand how larger scale systems like multifamily and hotel systems might function. The system should be compared to a fully mixed one taking cold and hot sources, as well as to a simple analysis of the pass-through heat exchangers used to pre-heat the cold-source input of shower water. Finally, the current view of the heat pump is very simplified. Collaboration is being developed with a group from the Lucerne Univ. of Applied Science and Arts. This will lead to a better understanding of the real potential operation of a heat pump using the waste heat recovery scheme described. The initial experimentation in Lucerne and prototyping of the system with Geberit AG will provide an initial idea of the real costs of the system.

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